The Astrophysical Journal, 604:L45–L48, 2004 March 20

THE LINK BETWEEN WARM MOLECULAR DISKS IN MASER NUCLEI AND STAR FORMATION NEAR THE BLACK HOLE AT THE GALACTIC CENTER

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Received 2004 January 15; accepted 2004 February 6; published 2004 February 26

ABSTRACT

The discovery of hundreds of young, bright stars within a parsec from the massive black hole Sagittarius A* at the center of the Galaxy presents a challenge to star formation theories. The requisite Roche densities for the gravitational collapse of gas clouds are most naturally achieved in accretion disks. The water maser sources in Keplerian rotation in the nuclei of NGC 4258, NGC 1068, and the Circinus galaxy indicate the presence of warm, extended, molecular accretion disks around black holes similar in mass to Sgr A*. Here we argue that the current conditions in the maser nuclei, and those near the Galactic center, represent two consecutive, recurrent phases in the life cycle of the nucleus of a typical gas-rich spiral bulge. The warm molecular disks that give rise to the observed maser emission fragment into stellar-size objects. The stellar masses, their orbital geometry, and the total number of stars thus formed are consistent with the values identified at the Galactic center. The stars tend to form in compact groups resembling the IRS 13 complex that dominates the stellar light in the neighborhood of Sgr A*.

Subject headings: accretion, accretion disks — galaxies: nuclei — Galaxy: center — masers — stars: formation

1. INTRODUCTION

The dynamical sphere of influence of the massive black hole (MBH) at the Galactic center, measuring 1 pc in radius, is host to a large number of luminous, massive, and hence young stars (e.g., Krabbe et al. 1995; Genzel et al. 2000). The closest star to the MBH with detailed proper-motion data, S0-2, has an apocenter distance of only ∼0.01 pc and an eccentricity of ∼0.88 (e.g., Schödel et al. 2002). It is a B0–O8 dwarf with a mass of 10–15 $M_\odot$ and an age of $\lesssim$10 Myr (Ghez et al. 2003a). A number of other stars at radial distances $\lesssim$0.03 pc exhibit properties similar to those of S0-2 (e.g., Ghez et al. 2003b). At a projected distance $\gtrsim$0.1 pc from the MBH, a cluster containing seven blue supergiants, known as the IRS 13 complex, dominates the ionizing luminosity (e.g., Najarro et al. 1997). At somewhat larger distances of 0.1–0.5 pc, as many as ∼40 Wolf-Rayet stars have been observed (Genzel et al. 2003). Since the zero-age main-sequence (ZAMS) mass of the Wolf-Rayet stars is 30–100 $M_\odot$, this implies that the Galactic center had been host to a recent starburst with a total initial stellar mass of greater than 10^3 $M_\odot$.

Various dynamical mechanisms by which young stars could have migrated from larger radii into a fraction of the central parsec have been considered (Gerhard 2001; Gould & Quillen 2003; Kim & Morris 2003). None are successful at explaining the observed concentration of young stars, unless an additional, hitherto undetected dynamical component, such as an intermediate-mass black hole, is invoked (Hansen & Milosavljević 2003). This conclusion, therefore, suggests that the stars have probably formed in situ. Molecular cloud densities of 10^{14} cm^{-3} at the radius corresponding to the apocenter distance of S0-2, and those of 10^9–10^{10} cm^{-3} at the orbital radii of the Wolf-Rayet stars, are required for gravitational collapse to occur in the presence of the Sagittarius A* tide (Morris 1993). The densities of molecular cloud fragments found in the central 2 pc of the Galaxy, however, do not exceed ∼10^6 cm^{-3} (e.g., Jackson et al. 1993).

The densities necessary for gravitational collapse in the tidal field of the MBH could easily be sustained in accretion disks. The young stars may be connected to a past accretion disk at the Galactic center since their orbits appear to lie within one or more distinct planes (Levin & Beloborodov 2003; Genzel et al. 2003). Multiple stellar disks have been observed in the nuclei of other galaxies at the resolution-limited radii of ∼20 pc (e.g., Pizzella et al. 2002).

The proposal that stars form in the outer parts of accretion disks of active galactic nuclei (AGNs) is not new (Kolykhalov & Syunyaev 1980). The disks are susceptible to self-gravitating instability when the Toomre (1964) parameter $Q = c_s\Omega/\pi G\Sigma$ is less than unity, where c_s is the sound speed, $\Omega = (GM_{\rm bh}/r^3)^{1/2}$ is the angular velocity (assuming a Keplerian potential), $M_{\rm bh}$ is the mass of the MBH, and Σ is the surface density of gas. For a range of disk parameters, the disk fragments into stellar-size clumps. Shlosman & Begelman (1989) discussed star formation in cold, molecular disks of AGNs. Grains in the surface layer of a disk absorb the incident optical-to-soft X-ray flux from the AGN and reradiate it in the infrared. The disk bulk temperature remains low; e.g., if the 4×10^6 $M_\odot$ black hole at the Galactic center were accreting at the Eddington rate during a past accretion episode, it would have heated the disk to temperatures $\sim 36 r_3^{-1/2}$ K, where $r = 0.3 r_3$ pc is the distance from the MBH. Such a cold disk is self-gravitating at surface densities $\gtrsim$5 g cm^{-2}. The apparent inevitability of fragmentation implies a crisis for the extended disk models (Goodman 2003).

While the construction of extended disk models may be challenging, nature offers evidence that these disks indeed exist. Maser emission in the rotational level transition $6_{16} \rightarrow 5_{23}$ of water has been detected at 22 GHz in the nuclei of several Seyfert II and LINER galaxies. Keplerian rotation patterns and disklike geometries of the maser sources at distances $\gtrsim$0.1 pc from the MBH have been detected in (at least) three cases: NGC 4258 (Miyoshi et al. 1995; Greenhill et al. 1995), NGC 1068 (Gallimore et al. 1996), and the Circinus galaxy (Greenhill et al. 2003a; Greenhill et al. 2003b). This has provided an accurate

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mass determination for the central black holes as well as the distances to some host galaxies (e.g., Herrnstein et al. 1999).

In Table 1, we summarize the inferred values of the black hole mass $M_{\rm bh}$, the radii of the masing sources from the MBH $r_{\rm disk}$, and the stellar velocity dispersions $\sigma_{\rm stellar}$ of the host bulges. Note that in all cases, the masers are located within the spheres of dynamical influence of the MBH $r_{\rm disk} < GM_{\rm bh}/\sigma^2_{\rm stellar}$, which reflects the selection of these sources for nearly Keplerian rotation patterns.

The purpose of this Letter is to highlight a connection between the warm molecular disks in AGNs and the stellar populations at the Galactic center. In § 2, we review the thermodynamical properties of a warm molecular disk by assuming that the conditions in this disk are uniformly conducive to the production of water maser emission. In § 3, we study the fragmentation of the disk and the formation of stars.

2. CONDITIONS IN THE DISK FROM THE REQUIREMENTS FOR MASER ACTION

An inverted population of the maser levels, which is a precondition for maser action, requires a minimum gas temperature of 400 K (e.g., Maloney 2002; Watson 2002). Collisional pumping of the levels requires that the density of the masing gas be at least 10^7 cm^{-3}. Above 10^{10} cm^{-3}, the levels are thermalized, and the maser action is quenched. We assume that the conditions for the operation of masers are homogeneously represented in the disk, and we adopt the fiducial temperature $T_{\rm gas} = 400$ K and density $n_{\rm gas} = 10^9$ cm^{-3} at a distance $r_{\rm disk} \sim 0.3$ pc from a central black hole of mass $M_{\rm bh} \sim 10^7\ M_\odot$. We defer discussing the origin of the unexpectedly high temperature of the molecular gas to § 4.

The assumption that the accretion disk has, on average, the same parameters as the masing regions is not essential; i.e., the masing regions could be localized condensations in the disk (§ 4). The star formation mechanism presented in § 3, however, is valid even at average temperatures of less than 400 K.

The vertical scale height of a disk in pressure equilibrium is $H = c_s/\Omega = \Sigma/\mu m_{\rm H_2} n_{\rm gas}$, where the isothermal sound speed of gas with a mean molecular weight μ in units of the hydrogen molecular mass is related to the temperature via $c_s^2 = kT_{\rm gas}/\mu m_{\rm H_2}$. The vertical column density of nuclei amounts to $\Sigma/m_{\rm H} \approx 8.5 \times 10^{24} \mu^{-1/2} n_9 T_4^{1/2} r_3^{3/2} M_7^{-1/2}$ cm^{-2}, where $n_{\rm gas} = n_9 \times 10^9$ cm^{-3}, $T_{\rm gas} = 400 T_4$ K, and $M_{\rm bh} = M_7 \times 10^7\ M_\odot$.

Note that very similar column densities of 10^{25} cm^{-2} and 4×10^{24} cm^{-2} have been inferred from hard X-ray absorption measures in the nuclei of NGC 1068 (Matt et al. 2004) and the Circinus galaxy (Matt et al. 1999), respectively. This coincidence lends support to our characterization of the conditions in the disk. Detailed comparison, however, is not possible because the inclination and the corresponding absorbing column densities depend sensitively on the unknown degree of warping in the observed disks.

3. FORMATION OF STARS IN A WARM MOLECULAR DISK

Since $H/r \sim 0.003 (T_4 r_3/\mu M_7)^{1/2}$, the disk is geometrically thin, and its gravitational stability can be determined by evaluating the Toomre parameter $Q = 2.6 n_9^{-1} r_3^{-3} M_7$. We find that Q drops below unity outside the critical radius of $\sim 0.42 (M_7/n_9)^{1/3}$ pc. The critical radii coincide, to within the uncertainty in $n_{\rm gas}$, with the radii of the observed maser disks.

Fragmentation of a marginally unstable disk produces gravitationally bound objects of the Jeans mass $M_{\rm Jeans} = c_s^4/G^2 \times \Sigma \sim 3\mu^{-5/2} n_9^{-1} T_4^{3/2} r_3^{-3/2} M_7^{1/2}\ M_\odot$. The Jeans length is approximately equal to the disk thickness, which is in turn equal to the Hill (Roche) radius $R_{\rm H} = (m_*/3M_{\rm bh})^{1/3} r$ of a newly formed self-gravitating object of mass m_* (hereafter a "protostar").

TABLE 1
Inferred Values

Galaxy	$M_{\rm bh}$ ($10^7\ M_\odot$)	$r_{\rm disk}$ (pc)	$\sigma_{\rm stellar}$ (km s^{-1})
NGC 4258 ……	3.9[a]	0.16–0.28[a]	167[b]
NGC 1068 ……	1.0[c]	>0.6[d]	177[b]
Circinus ………	0.17[e]	0.11–0.4[e]	167[b]
Milky Way ……	0.4[f]	…	75–125

[a] Herrnstein et al. (1999).
[b] Prugniel & Simien (1996).
[c] Greenhill et al. (1996).
[d] Gallimore et al. (2001).
[e] Greenhill et al. (2003b).
[f] Ghez et al. (2003b).

The total disk mass $\pi r_{\rm disk}^2 \Sigma$ within the radius of the masers is $M_{\rm disk} \sim 1.3 \times 10^4 \mu^{1/2} n_9 T_4^{1/2} r_3^{7/2} M_7^{-1/2}\ M_\odot$. This mass is comparable to the conservative estimates of the mass of the circumnuclear disk (CND) at the Galactic center (Mezger, Duschl, & Zylka 1996 and references therein).

The maximum number of separate protostars that can be produced by the Jeans instability is then $N_{\rm max} \sim M_{\rm disk}/M_{\rm Jeans} \sim 4300 f \mu^3 n_9^2 r_3^5 / T_4 M_7$, where f is the fraction of the disk mass that undergoes fragmentation. We expect that the latter fraction is well below unity, e.g., $f \sim 0.1\%$–1%. The density wakes associated with the Lindblad resonances of the protostars that formed first stimulate further fragmentation (Armitage & Hansen 1999; Lufkin et al. 2004).

Gas interior to the Hill annulus $|\Delta r| \lesssim R_{\rm H}$ in the disk is delivered by differential rotation into the protostar's Roche lobe and can accrete onto the star. The final mass of the protostar can thus be much larger than the Jeans mass. Equating the total mass in the annulus $2\pi r R_{\rm H} \Sigma \propto m_*^{1/3}$ to the mass of the protostar m_* and solving for the latter yield the maximum "isolation mass" (Lissauer 1987) $M_{\rm iso} \sim (4/3\pi) M_{\rm disk}^{3/2}/M_{\rm bh}^{1/2}$ to which the star can grow by accreting the disk material. In gaseous protoplanetary disks, the growth of a planet terminates when a gap of width $\gtrsim R_{\rm H}$ opens in the disk. In AGN disks, however, $M_{\rm iso}$ is a large fraction of $M_{\rm disk}$ (Goodman & Tan 2003).

If multiple Jeans patches of the disk collapse simultaneously, their Hill annuli grow until they overlap. The accretion is terminated either by reaching the isolation mass or by the global depletion of gas from the accretion onto multiple protostars.

Before the protostellar mass has reached the terminal value, differential rotation in the disk delivers disk material into the Hill sphere of the protostar at the rate $\dot{m}_* \sim R_{\rm H}^2 \Sigma \Omega$, or

$$\dot{m}_* \sim (10^{-4}\ M_\odot\ {\rm yr}^{-1}) \mu^{1/2} \left(\frac{m_*}{3\ M_\odot}\right)^{2/3} \frac{n_{\rm gas}}{10^9\ {\rm cm}^{-3}} \times \left(\frac{T_{\rm gas}}{400\ {\rm K}}\right)^{1/2} \left(\frac{r_{\rm disk}}{0.3\ {\rm pc}}\right)^2 \left(\frac{M_{\rm bh}}{10^7\ M_\odot}\right)^{-2/3}. \quad (1)$$

If the protostar could accept mass at this rate, its growth time would be given by $m_*/\dot{m}_* \sim 2.5 \times 10^4 \mu^{-1/2} m_3^{1/3} M_7^{2/3} r_3^{-2} n_9^{-1} T_4^{-1/2}$ yr.

The gas arriving into the Hill sphere undergoes a shock near the L1 and L2 Lagrangian points and forms two streams around the protostar (Lubow, Seibert, & Artymowicz 1999; Bate et al. 2003). The streams circularize at a fraction of ~50% of $R_{\rm H}$ from the protostar. The protostar is therefore fed from an accretion disk of its own. We have made an implicit assumption that the entire mass entering the Hill sphere on horseshoe orbits is inelastically captured and remains inside the sphere.

Gas in the protostellar disk must be able to dispense its angular momentum if it is to contract onto a central protostellar core. The radial extent of the protostellar disk is large, $\log(R_H/2R_*) \gtrsim 4$, where R_* is the radius of a star of mass m_* on the ZAMS. In a purely gaseous disk, angular momentum extraction could be achieved via radial transport ("α-viscosity"; Shakura & Sunyaev 1973) driven by the magnetorotational instability (MRI; Balbus & Hawley 1998), via the magnetic breaking (MB) mechanism (e.g., Mouschovias & Paleologou 1979), or via the centrifugal launching of winds from the disk surface (Blandford & Payne 1982).

MRI and MB are expected to operate in the outermost region of the protostellar disk if the concentration of free electrons in the gas is sufficiently large to provide for an inertial coupling with a magnetic field. This concentration depends on the detailed chemistry that we do not attempt to analyze here. We are thus not in the position to decide whether the outer edge of the protostellar disk is magnetically "dead" or "active." If it is dead, the material captured inside the Hill sphere accumulates in a violently unstable ring around the protostar. If it is active, it is, in principle, possible that a magnetically mediated angular momentum extraction maintains gravitational stability in the protostellar disk. For example, Papaloizou, Nelson, & Snellgrove (2003) found evidence of MB while simulating the accretion onto planetary embryos embedded within a protostellar disk with ideal magnetohydrodynamics (IMHD). We proceed to check for gravitational stability assuming, optimistically, that IMHD is realized in the protostellar disk.

If MRI is the dominant angular momentum extraction channel, and if the accretion rate is given by equation (1), the disk parameters can be evaluated in the standard fashion (e.g., Frank, King, & Raine 2002). In the optically thick, adiabatic limit, we have $\alpha = 0.01\alpha_{-2}$ with $\alpha_{-2} \sim 0.1$–1 (e.g., Sano et al. 2003). The Rosseland mean opacity of molecular gas above 100 K and below the opacity gap at ∼1000 K is in the range $\kappa \sim 2$–10 $\mathrm{cm^2\ g^{-1}}$ (Pollack et al. 1994; Semenov et al. 2003). Assuming that the outer radius of the disk is $\sim R_H$, the Toomre parameter there equals $Q_* \sim 0.0075\mu^{-1.4}\alpha_{-2}^{0.7}\kappa^{0.3}M_7^{0.72}r_3^{-2.2}m_3^{-0.27}n_9^{-0.4}T_4^{-0.2}$. (All other parameters pertain to the parent, AGN disk medium.) The outer edges of an α-protostellar disk are thus gravitationally unstable in their own right.

If MB is the dominant angular momentum extraction channel, the angular momentum is removed in a vertical Alfvén crossing time of the disk, $t_{mb} \sim \phi^{-1}\rho_{gas}^{-1/2}$, where $\phi \sim B_{unif}/\Sigma$ is the specific magnetic flux threading the gas in the donor AGN disk, ρ_{gas} is the ambient gas density (here assumed to equal the density of gas in the donor disk), and B_{unif} is the net magnetic field threading the disk. If B_{unif} is a fraction ξ of the equipartition field $(4\pi\rho_{gas})^{1/2}c_s$, then $\phi = 2\xi\Omega\,(\pi/\rho_{gas})^{1/2}$. From mass and flux conservation in the flux-freezing approximation, we get that the column density in the protostellar disk Σ_* is related to that in the AGN disk via $\Sigma_* = \Sigma/\xi$. Thus, assuming a uniform gas temperature, the Toomre parameters of the two disks are related via $Q_* = \xi Q$. Since $Q \sim 1$ and $\xi \ll 1$, we expect $Q_* \ll 1$. Again, the protostellar disk is gravitationally unstable.

We have found that the protostellar disk is susceptible to fragmentation in its own right and separates into multiple clumps. This process has recently been identified in simulations (Boss 2002; Nakamura & Li 2003; Machida, Tomisaka, & Matsumoto 2004). While the Hill sphere continues to receive gas at the rate given by equation (1), this gas does not accrete to a single protostar but to a group ($N_{group} \geq 2$) of protostars sharing the same Hill sphere. If $N_{group} \gtrsim 3$, the spatial extent of the group increases because of the strong two-body encounters ("dynamical evaporation") beyond the original Hill sphere. The evaporation takes place on a timescale of $\sim\Omega^{-1}N_{group}$. The final group does not share the same Hill sphere even if the initial group did, and it is tidally stretched.

Evidence that stars form in compact groups can be found at the Galactic center. The IRS 13 complex is located at the projected distance of $\sim 3'' \approx 0.12$ pc from Sgr A* and has an apparent diameter of less than 0.04 pc. This compact stellar cluster contains seven blue supergiants. Recently, additional candidate members of this or a similar group have been discovered (Eckart et al. 2003). Assuming an inclination of IRS 13 relative to Sgr A* of 45° and an initial Hill radius of ∼0.01 pc, the spatial extent of IRS 13 would correspond to a Hill sphere associated with a total mass of $\sim 2500\ M_\odot$. This is a fraction of the mass of the present CND and is compatible with the isolation mass limit for a $3 \times 10^4\ M_\odot$ disk that would form if the CND were to start accreting toward the MBH.

The stars forming in the disk possess initially quasi-circular orbits, yet several of the most bound stars, including S0-2, exhibit high eccentricities $e \gtrsim 0.8$. While the disk torques are not effective at generating such high eccentricities, nearby encounters between stars could, in principle, scatter stars onto radial orbits. An encounter between stars initially belonging to disjoint Hill annuli induces a velocity change $\Delta v \sim (Gm/R_H)^{1/2} \sim (m/M_{bh})^{1/3}r\Omega$, which is much too low to deflect the star by of order its own velocity, $\sim r\Omega$, required for $\Delta e \sim 1$. Significantly larger velocity kicks result from three- or four-body gravitational slingshot interactions between *binary* stars sharing the same Hill sphere (massive stars in the field generically form in compact binaries; e.g., Vanbeveren, de Loore, & van Rensbergen 1998). Indeed, the circular velocity at S0-2's apoapse, $\sim 1300\ \mathrm{km\ s^{-1}}$, is comparable to the maximum velocity that a 15 $M_\odot$ star can be deflected by, while avoiding direct collision with a similar star.

4. DISCUSSION

So far, we have avoided explaining how the high temperature (∼400 K) can be maintained in the maser disk. Dissipation of turbulence within the disk is not effective in this regard (Neufeld & Maloney 1995; Desch, Wallin, & Watson 1998). To demonstrate this, we search for the (unrealistic) value of α that would be necessary to power the masing disk from within. The vertical optical depth equals $\tau = \kappa\Sigma \sim 10\mu^{1/2}\kappa n_9 T_4^{1/4}M_7^{-1/2}r_3^{3/2}$. The accretion time $t_{acc} = \pi r^2\Sigma/\dot{M}$ is larger by 10^3–10^5 than the dynamical time. Thus, the accretion rate $\dot{M} = 3\pi\alpha c_s^2\Sigma/\Omega$ may be very different at different radii (Gammie, Narayan, & Blandford 1999) and need not be related to the bolometric luminosity of the AGN. Instead, we assume that n_{gas} and T_{gas} are independent variables and obtain $\alpha \sim 750\kappa^{-1}n_9^{-1}T_4^2M_7^{1/2}r_3^{-3/2}$. This requirement is orders of magnitude larger than the value typically found in numerical simulations. Therefore, the standard α-disks are not sufficiently warm to form masers.

Next, we check whether or not the protostellar radiative output could heat the disk. Part of the residual disk gas is accessible to the ionizing radiation from the new stars. Stars with ZAMS masses $\gtrsim 8\ M_\odot$ ionize the ambient hydrogen within $\sim 10^5$ yr from their initial collapse (e.g., Yorke 1986) and create H II regions within their parent disk. The characteristic region size is given by the Strömgren radius $R_S = (3\mathcal{F}/4\pi n_H^2\alpha_B)^{1/3}$, where $\mathcal{F}$ is the number of ionizing photons per unit time emitted by the star and $\alpha_B \approx (2.6–4.5) \times 10^{-13}$ cm^3 s^{-1} is the case B recombination coefficient of hydrogen (Osterbrock 1989). The ionizing photon number flux for a star with an effective temperature T_* equals $\mathcal{F} \approx 16\pi^2 kT_* R_*^2 \nu_0^2 c^{-2} h^{-1} e^{-h\nu_0/kT_*}$, where $h\nu_0 = 13.6$ eV. Taking the stellar luminosity $L_* \approx (15{,}000\ L_\odot) m_8^3$, where $m_8 = m_*/8\ M_\odot$ and stellar radius $R_* \approx (3.2\ R_\odot) m_8^{0.56}$, we get $R_S \approx 4 \times 10^{14} \sqrt{m_8} e^{-1.5/\sqrt{m_8}} n_9^{-2/3}$ cm.

The H II region is much smaller than the disk radius even if ∼99% of the disk gas has been depleted. The resulting H II distribution has a "blister" geometry typically found in the Orion Nebula and in other star-forming regions (SFRs). In SFRs, maser sources are found in the shocked, dense shell of the blister. The isotropic luminosities of the SFR masers, $\sim 10^{-3}$ to 1 $L_\odot$, are much smaller than those of the circumnuclear masers, $\sim 10–10^3\ L_\odot$. This may be the result of a longer gain path along coherent velocity patches in the AGN disk (where the gas flow is organized) rather than a larger pumping luminosity (e.g., Deguchi & Watson 1989).

The stars could also heat the disk gas mechanically, by driving spiral density waves that in some circumstances lead to spiral shocks. Such coherent, spiral shocks in the disk have been proposed as the sites of maser emission (Maoz & McKee 1998). This explanation, however, depends on many details of the model that we do not attempt to investigate here. The most promising mechanism for heating the disk gas may still be illumination by the X-ray flux of the AGN (Neufeld, Maloney, & Conger 1994). The X-rays heat a surface layer in the disk while allowing the midplane to remain cooler. If the average midplane temperature of the disk were, say, ∼5 times lower then the Jeans mass would have been, $M_{\rm Jeans} \sim 0.27\ M_\odot$. The subsequent evolution described in § 3, including the rapid accretion of disk gas, the subfragmentation into multiple stars sharing the same Hill sphere, and the global depletion of disk gas, would occur in the same fashion.

We thank A. Barth, R. Blandford, P. Goldreich, J. Moran, S. Phinney, F. Rasio, R. Sari, and R. Sunyaev for inspiring discussions and W. Watson for valuable comments. The research of M. M. was supported at Caltech by a postdoctoral fellowship from the Sherman Fairchild Foundation. This work was also supported in part by NASA grant NAG5-13292 and by NSF grants AST 00-71019 and AST 02-04514 to A. L.

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